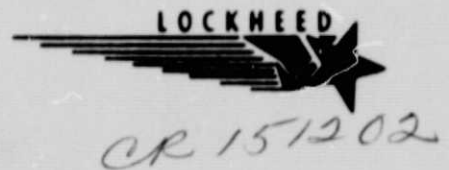


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LMSC HREC TR D497190



# SPACE SHUTTLE PLUME AND PLUME IMPINGEMENT STUDY

**Final Report**

**Contract NAS9-14845**

**March 1977**

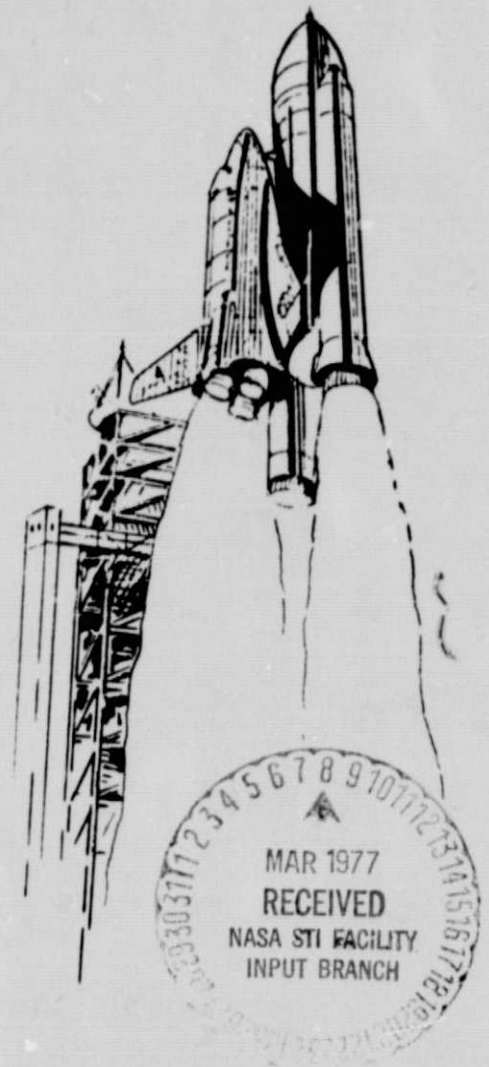
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## FOREWORD

This report is a summary of the results of work performed by the Lockheed-Huntsville Research & Engineering Center in fulfillment of the requirements of Contract NAS9-14845 with NASA-Johnson Space Flight Center, Houston, Texas, in support of Space Shuttle related exhaust plume applications. The contracting officer's technical representative for this study was Mr. Barney B. Roberts of the Aerodynamic Systems Analysis Section.

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## Section 1 INTRODUCTION

Current configurations of the Space Shuttle vehicle utilize a combination of liquid and solid propellant booster motors to provide vehicle thrust during the launch phase. Rocket exhaust plumes from the Space Shuttle main engine (SSMEs) and solid rocket boosters (SRBs) have been found to significantly affect vehicle aerodynamics by plume-induced flow separation. Vehicle performance is impacted by plume-induced base pressure drag. Solid propellant motors are used to effect separation of the booster motors from the orbiter. Interaction of the exhaust plumes from these motors with the external surroundings produce hostile environments which must be considered in the vehicle design phases.

The extent of the influence of the propulsion system exhaust plumes on the vehicle performance and control characteristics is a complex function of vehicle geometry, propulsion system geometry, engine operating conditions and vehicle flight trajectory. This interaction is defined by scale model launch vehicle test programs. These test programs utilize a "cold" gas and subscale nozzles to simulate the various exhaust plumes. Similarity parameters are applied to determine the subscale operating conditions necessary to simulate the full-scale plume conditions. Exhaust plume simulation requires that three basic problem areas be considered: (1) definition of the full-scale exhaust plume characteristics; (2) application of appropriate similarity parameters; and (3) analysis of wind tunnel test data.

Analytical support of the plume technology test program was directed at the two latter problem areas. Verification of the two-phase plume and plume impingement models was directed toward the definition of the full-scale exhaust plume characteristics and the separation motor impingement problem.

## Section 2

### TASK SUMMARIES

The tasks performed under this contract were directed toward: (1) verification of the two-phase plume flowfield and plume impingement models, and (2) analytical support of the plume technology test program. These tasks are summarized in the following discussion.

#### 2.1 VERIFICATION OF TWO-PHASE PLUME AND PLUME IMPINGEMENT MODELS

Numerical solutions have been developed to calculate the exhaust plume flow fields of solid propellant rocket motors and the pressure and thermal environments experienced by bodies immersed in these two-phase plumes. These numerical solutions are incorporated in the Lockheed-Huntsville RAMP and PLIMP computer codes (Refs. 1 and 2). The RAMP code was developed by extending an existing nozzle-exhaust plume solution to include the treatment of two-phase flows. Modeling of two-phase effects relied heavily on the previous work of Kliegel, which has been extended to include reacting gas chemistry. Solid particle data used in the two-phase analysis are empirical and were developed primarily for nozzle performance applications. Because the RAMP computer code is being used to specify Space Shuttle design criteria, it was necessary to confirm the validity and accuracy of the code's empirical input data and calculational scheme. Previous experimental measurements of gas-dynamic properties in solid propellant rocket exhaust plumes were insufficient in quantity and quality to provide the necessary experimental data base. A test program was conceived to provide the necessary experimental data. Analysis of the test program data was intended to accomplish the following:

- Confirm the RAMP numerical flowfield solution.
- Confirm the analytical thermochemical model.
- Validate the solid particle empirical input data.
- Validate the two-phase plume impingement model.

The test program used subscale solid propellant rocket motors with operating parameters typical of full-scale applications. Rocket motor operating parameters and test measurements were parametrically varied to provide a coherent but diverse data base. Multiple rocket firings were performed for each test condition to confirm experimental repeatability and raise the confidence level of the data. The following document presents the results of an analysis of this test program data.

- Assessment of Analytical Techniques for Predicting Solid Propellant Exhaust Plumes and Plume Impingement Environments (Ref. 3)

Results are presented of an analysis of experimental nozzle, exhaust plume and exhaust plume impingement data. The data were obtained for subscale solid propellant motors with propellant Al loadings of 2, 10 and 15% exhausting to simulated altitudes of 50,000, 100,000 and 112,000 ft. Analytical predictions were made using the RAMP and PLIMP computer codes.

Comparisons of experimentally measured and analytically predicted nozzle wall static pressures are presented for each propellant Al loading. Radial distributions of pitot pressure and heating rates measured experimentally at axial stations of  $x/D_{\text{exit}} = 5, 12, 16$  and  $20$  are compared with analytical predictions. Experimental plume impingement pressures and energy fluxes were obtained for a flat plate immersed in the exhaust plumes at various angles of attack and centered at axial stations of  $x/D_{\text{exit}} = 5, 12$  and  $20$ . Analytical predictions of the thermal and pressure environments on the flat plate are compared with the experimental data.

The validity of the empirical data input to the analytical calculations is investigated. The effects of mass mean particle size, particle size distribution and particle drag model on the comparison of experimental and analytical exhaust plume data are presented. Requirements for the adequate thermochemical modeling of two-phase nozzle and exhaust plume expansions are discussed.

## 2.2 ANALYTICAL SUPPORT OF PLUME SIMULATION TECHNOLOGY PROGRAM

To account for the effects of the SSME and SRB exhaust plumes on the Space Shuttle launch vehicle, the plumes must be simulated in the aerodynamic wind tunnel testing of the vehicle. High pressure air is expanded through subscale nozzles to generate gaseous exhaust plumes for the subscale wind tunnel models. The plume technology test program was conducted to generate a matrix of plume simulation data for this application. The data are used to develop similarity parameters for designing launch vehicle test programs and conducting post-test application studies. A number of subscale nozzles were designed and constructed for use in the test program. Definition of the nozzle exit properties and plume expansion characteristics is necessary for correct application of the plume technology data to the simulation of prototype exhaust plumes. The following document summarizes the analytical effort to define the technology program nozzle exit properties.

- Exit Properties and Initial Plume Expansion Characteristics of Nozzles Used in the Plume Technology Test Program (Ref. 4)

Eighteen subscale nozzle geometries were used in the plume technology program. For the analytical calculation of nozzle exit and lip expansion properties, the measured nozzle geometries are used to define the nozzle contours. Several working fluids are expanded through the technology program nozzles. Freon 14 ( $\text{CF}_4$ ) is used as the prototype gas to simulate the expansion properties of the full-scale SSMEs and SRBs. Air is used to simulate the prototype gas. Helium is an alternate simulant gas. Two solid propellants with 16% aluminum loading, UTP-3001 and LPC-5800, and one propellant with 2% aluminum loading, ANB-3335, are used to simulate the effects of two-phase exhaust plumes.

A method-of-characteristics solution incorporated in the MOC computer code (Ref. 5) is used to calculate the nozzle flow fields and lip expansions for the nozzles flowing air,  $\text{CF}_4$  and helium. The RAMP computer code (Ref. 1) is used to calculate the two-phase nozzle flow fields and lip expansions. A



constant property model ("ideal gas") is used to define the thermodynamic properties of the air and helium expansions. A thermodynamic model using a non-standard equation of state (Ref. 6) defines the thermodynamic properties of the  $\text{CF}_4$  expansions. Tables of thermodynamic properties for each solid propellant are calculated with the TRAN72 computer code (Ref. 7) to define the gas-phase thermodynamics in the two-phase expansions.

The analytical nozzle wall static pressure distribution for each nozzle is compared with available experimental data. If the data comparisons are within acceptable tolerance limits, the calculated nozzle exit conditions are expanded through the Prandtl-Meyer fan at the nozzle lip to a low pressure. If the data comparisons are unacceptable, the experimental data are accepted as correct and the nozzle exit conditions are adjusted to the experimental value. The corrected exit conditions are expanded through the Prandtl-Meyer fan to a low pressure.

The nozzle exit properties are tabulated and the Prandtl-Meyer expansion properties plotted for each nozzle geometry and working fluid. Thermodynamic properties of the  $\text{CF}_4$  and solid propellant expansions are a function of chamber temperature and pressure. These working fluids were expanded from a matrix of chamber conditions indicative of the range of conditions encountered in the plume technology test program.

## CONCLUSIONS

This study confirmed the validity of the two-phase plume flowfield model for solving Space Shuttle plume problems. The range of applicability of the two-phase plume impingement model was determined. The nozzle exit plane and lip expansion data for the plume technology test program nozzles will provide an excellent data base for pretest prediction and post-test analysis of the final Space Shuttle integrated aerodynamics test.

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